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Edible ink for food printing and packaging applications: a review

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The food industry has witnessed significant advancements in food printing and packaging. Edible ink is a major innovation, which has revolutionized the food industry by providing customized, attractive, and safe food printing solutions. This review article aims to explore various aspects of edible ink, including its composition, applications, and challenges. The study was conducted by analyzing current research articles and patents related to edible ink and food printing technology. This study revealed that edible ink is composed of food-grade materials and can be printed on different food surfaces, including cakes, cookies, and bread. Edible ink is used widely in the food industry, such as in the customization of cakes, chocolates, and pastries, labeling and branding of food products, and printing of food-based images for special occasions. We also highlighted the challenges associated with using edible ink, such as its limited color range and printing resolution. Nonetheless, edible ink has emerged as a game-changing technology in the food industry that offers innovative and safe food printing and packaging solutions. Despite the challenges associated with its use, the benefits of edible ink outweigh its limitations. Further research is required to overcome the limitations associated with the use of edible ink and to explore its new applications in the food industry.

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Sustainability spotlight

This review paper, titled "Edible Ink for Sustainable Food Printing and Packaging Applications", delves into the intersection of technology and sustainability within the realm of food printing and packaging. The spotlight shines on the innovative use of edible ink as a key player in advancing sustainable practices in the food industry. By exploring the latest developments and applications, this paper underscores the potential of edible ink to revolutionize the way we produce, label, and package food. In a world increasingly conscious of environmental impact, this comprehensive review provides insights into the eco-friendly aspects of edible ink technology, emphasizing its potential to reduce waste and minimize the environmental footprint of food packaging. By shedding light on the sustainable attributes of edible ink, the paper contributes to the ongoing discourse on fostering environmentally responsible practices in the food sector. As we navigate the challenges of the modern food industry, this Sustainability spotlight statement invites readers to contemplate the role of edible ink as a catalyst for positive change. Through this exploration, we hope to inspire further research and innovation, ultimately steering the food industry towards a more sustainable and responsible future.

1. Introduction

Currently, edible inks are increasingly being used for food printing and packaging applications in the food industry. This technology has enabled food manufacturers to create unique designs, patterns, and logos for food products, which not only enhances the aesthetics of the product, but also provides valuable information to consumers.[1,2] The use of edible ink has opened new opportunities for food manufacturers to differentiate their products from competitors, which is becoming increasingly important in a highly competitive market.[3] Edible inks are inkjet inks specifically designed for food printing and packaging applications. These inks are made from Food and Drug Administration (FDA)-approved food dyes that are safe for human consumption.[4] The ink is printed on the food surface using specialized printers that are capable of printing intricate designs and patterns on various food substrates. The use of edible inks is not only limited to printing on food products, but can be extended to printing on edible paper, wafer paper, and icing sheets.[5]

The development of edible ink technology has come a long way since its inception. The earliest forms of edible ink were made from vegetable dyes and were limited in color range and print quality.[6,7] However, advancements in technology have led to the development of high-quality edible inks capable of producing vibrant colors and intricate designs of food products.[8] The use of edible ink has evolved from printing logos and patterns on food products to printing of QR codes, barcodes, and other information on food packaging.[9] The benefits of using edible ink for food printing and packaging applications are numerous. First, it allows food manufacturers to create unique designs and patterns for food products, which can help differentiate their products from competitors.[10–12] This is particularly important in a highly competitive market, where product differentiation is crucial. Second, it provides valuable information to consumers, such as information regarding nutrition and ingredients, and allergy warnings.[13–15] This is particularly important for consumers with food allergies and dietary restrictions. Third, the use of edible ink can enhance the overall aesthetics of a product, making it more visually appealing to consumers.[7,16]

However, certain challenges are associated with the use of edible inks. The printing process requires specialized printers designed to handle food substrates, which are expensive and require regular maintenance.[17,18] Additionally, the cost of edible

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inks can be higher than that of traditional inkjet inks because of the use of FDA-approved food dyes. Furthermore, certain regulatory requirements must be adhered to when edible inks are used in food products.[19]

In this review, we have discussed the different components of edible ink, methods of extraction of colorant/dyes from natural sources, and various preparation methods for edible ink. We have also briefly discussed the rheological and antimicrobial properties of edible ink. Different printing techniques, such as screen printing, flexography, inkjet printing, and three-dimensional (3D) printing, have been thoroughly reviewed. We also provided insights regarding the use of edible ink in food printing applications, along with its challenges and future prospects.

2. Composition of edible ink

Edible ink is typically formulated to be compatible with specific types of printers such as inkjet printers or dedicated edible ink printers. The ink composition may vary depending on the type of printer and printing technology used. However, some common ingredients can be used in edible inks.

2.1 Edible colorant

Edible colorants are food-grade dyes and pigments used to add color to various foods and beverages. These colorants are typically added in small amounts to enhance the appearance of a product, make it more visually appealing, or convey a particular flavor or message. Edible colorants play an essential role in the food industry, allowing the creation of visually appealing and attractive food products.[20–22] As consumer demand for natural and healthier ingredients continues to grow, emphasis on the use of natural colorants will increase in the future. Edible colorants are used in a wide range of food products, including baked goods, confectioneries, dairy products, beverages, and processed foods. The colors for edible ink are collected from different natural sources. Table 1 contains natural and synthetic colorants and dyes.

Titanium dioxide,[23] annatto, cutch, pomegranate rind, golden dock,[24] tartrazine, allura red, light blue, apple green, composite black,[25] red beet,[26] *Monascus*,[27] and TiO_2 (ref. 28) are the commonly used coloring agents. Natural colorants from plants, fruits, vegetables, and other sources exhibit different characteristics, such as antioxidant, antibacterial, anti-inflammatory, anti-oxidation, anti-mutation, anti-tumor, hepatoprotective, hypoglycemic, and medicinal properties, as shown in Table 2.

2.2 Mordant

Mordants are color enhancers that magnify color when mixed with edible colorants. In addition, mordants help in adhering to substrates and increase durability and lightfastness. They are also used as substances to fix or bind the colorants in the ink to the surface of the substrate being printed on. In the case of edible inks, mordants are used to ensure that the ink adheres to the surface of the food item being printed without bleeding or smudging. One common color enhancer used in edible ink is called “brilliant black”, which is a carbon-based substance that can enhance the intensity of black or dark colors. Another example is that of a brightening agent, such as titanium dioxide, which can be added to white ink to make it opaque and more vibrant.

Alum, potassium dichromate, ferrous sulfate, chrome, copper sulfate, zinc sulfate, iron, tannin, and tannic acid are some of the critical natural color enhancers used.[29–31] Ozcan *et al.* (2020) used potassium alum as a mordant while preparing edible ink. The ink with the mordant adhered better to the paper surface, which appeared more crimson and darker in color, and was resistant to acid treatment. When a mordant was applied to ink, the lightfastness values increases and the color difference decreases. Mordanting is advised to improve adherence of the color to the surface and its light resistant.[32]

2.3 Binder

Binders are substances used to hold the ingredients in ink together and to help the ink adhere to the substrate being printed. The binder plays a significant role in maintaining the stability and facilitating ink printing. Common examples of edible binders include gelatin, which is often used in jellies and gummies to give them a chewy texture, and cornstarch, which is used as a thickener in sauces and gravies.[33] Other examples of edible binders include modified food starch, gum Arabic, and carrageenan. The viscosity of the ink depends on the amount of

Table 1 Classification of colorants and dyes based on their origin

Classification	Colorant/dye
Natural	Plants: indigo (*Indigofera tinctoria*), woad (*Isatis tinctoria*), tyrian purple (*Purplehoemastroma/murex brandaris*), madder (*Rubia tinctorium*), henna (*Lawsonia inermis*), turmeric (*Curcuma longa*), weld (*Reseda luteola*), safflower (*Carthamus tinctorius*), annatto (*Bixa orellana*), black walnut (*Juglans nigra*), logwood (*Haematoxylum campechianum*), osage orange (*Maclura pomifera*), bloodroot (*Sanguinaria canadensis*), goldenrod (*Solidago* spp.), sumac (*Rhus* spp.), marigold (*Tagetes* spp.), red cabbage (*Brassica oleracea* var.) Animals: cochineal (*Dactylopisus coccus*), carmine (*Kermes vermilio*), sepia, shellac (*Kerria lacca*), guanine, oxblood, leather, patang (*Caesalpinia sappan*), lac (*Luccifer lacca*)
Synthetic	Aniline dye (coal tar), acid dye (acid red, acid blue and acid yellow), azo dye, disperse dye, direct dye, reactive dye, solvent dye, basic dye, vat dye, sulphur dye, anthraquinone dyes, phthalocyanine dye, triphenylmethane dye, quinoline dye, indigoid dye, dioxazine dye, quinacridone dye, metal complex dye

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Table 2 Sources, color, and functional properties of natural edible colorants

Edible colorant source	Color	Functional properties	Reference
Annatto seeds	Red	Antioxidants, antimicrobial, and medicinal benefits	29
Lichi rind	Red yellowish	Antioxidant and antibacterial	30
Purple heart	Purple	Antioxidant, antibacterial, and anti-inflammatory	32
Madder root	The queen of the reds	Medicinal benefits, cannot make edible ink because it is likely unsafe when taken by mouth, antioxidants and antimicrobial	97
Dragon fruit	Pink	Antioxidants and antimicrobial	98
Walnut rind	Brown	Antioxidants and antimicrobial	35
Sweet potato	Red at the pH range of 1.0–3.0, 1.0–3.0, became blue at 7.0–8.0, 7.0–8.0, then turned green at 9.0–10.09	Anti-oxidation, anti-mutation, anti-tumour, liver protection, hypoglycemia, and anti-inflammation	99
Carrot	Rich orange	Antioxidants and antimicrobial	36
Pandan leaf	Green	Antioxidants and antimicrobial	100
Mangosteen	Purple	Antioxidants, antimicrobial, and medicinal benefits	101
Guava leaf	Yellowish-brown	Antioxidants, antimicrobial, and therapeutic benefits	19
Orange peel	Green	Antioxidant and antibacterial	1
Pomegranate rind	Yellowish-brown	Antimicrobial	45
Turmeric	The most famous yellow colourant in the world	Antimicrobial and fastness properties	46
Red beet	Yellow-orange in primary state and pink-magenta in acidic	Antimicrobial and pH sensitive	48
Cutch	Reddish brown	Excellent color consistency and fastness	99
Golden dock	Yellow	Remarkable color consistency and fastness	99
Tartrazine, allura red	Yellow	Good droplet state and printing quality	36

binder used—screen printing ink requires more binder than other printing processes, such as flexography and gravure printing. The binder plays a vital role in maintaining the characteristics of the resulting ink such as adhesion, gloss, hardness, flexibility, runnability, and even the dispersal of the pigment. It is the vehicle component of printing inks and lacquers, either actively or after solvent treatment.[34]

Binder producers are constantly collaborating with ink industry players to develop new products that will aid in the creation of better and eco-friendly ink. Some end users demand the use of natural binders to produce food-grade inks. Sanson *et al.* (2007) developed screen printing ink and utilized Methocel A4M prem, MHEC 1500 PE, MHEP 20000P, and carboxymethyl chitosan (CMC) tylose as binders. The rheology of the inks was significantly influenced by the interactions between binders. In addition, a suitable binder system can avoid cracking during thermal treatment by imparting the required degree of elasticity to the applied film.[35] Savvidis *et al.* (2014)[24] used an ascospores LFD and sodium salt as binders. Huang *et al.* (2014)[25] utilized sorbitol and gum Arabic as edible binders. A good edible ink binder should be water-soluble, be of neutral pH, and sufficiently viscous to withstand ink jet printing demands. Sorbitol and gum Arabic have good solubility, pH, and viscosity, suitable for creating edible ink.

Viscosity is one of the crucial characteristics of inkjet ink, which significantly affects the calibration of the printing process. Binder content is the key element controlling ink viscosity.[36] Ozcan *et al.* (2020) used carboxymethyl cellulose as the binder. Binders are essential for maintaining the system and pigment stability, as well as for the printing process.[37] Zhang *et al.* (2016) used chitosan as a binder, which is ideal for preparing edible ink because of its superior qualities, including fineness, viscosity, dryness, tinting strength, and substrate adherence.[38] Shastry *et al.* (2011)[36] patented a water-based edible ink where shellac was used as a binder. They claimed that the binder can be easily distinguished from the adhesive agent applied to improve the compatibility of the ink for a specific surface in terms of both function and composition. In the absence of this mix, shellac has been proven to exert an unexpectedly positive impact on the drying time and picture quality.[39] The thickening and stabilizing qualities of xanthan gum, a polysaccharide produced from bacteria, make it a popular binder in recipes for edible ink.[40] Synthetic polymers like polypropylene glycol (PPG) and polyethylene glycol (PEG) are frequently employed to change the viscosity of ink and enhance printing capabilities.[41] As natural byproducts, potato flakes and mushroom scraps provide eco-friendly binders that support sustainable ink production operations. These

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components may improve the texture and substrate adherence of the ink in addition to serving as binding agents. Their use supports the movement in edible ink preparation toward the use of renewable resources and waste reduction, which is consistent with environmentally friendly printing techniques.[42]

2.4 Additives/solvents

Additives are used to increase the properties of the resulting ink and to change the ultimate qualities of the formulation, which are used either during ink manufacturing or during printing according to requirements. The viscosity of the printing ink depends on the amount of the additive or solvent used. Plasticizers, driers, waxes, surfactants, chelating agents, defoamers, pH modifiers, humectants, bacteriostats, biocides, reducers, binding varnish, anti-skinning agents, and cornstarch are commonly used additives in printing ink. While preparing edible ink, researchers must ensure that edible additives that are not harmful to humans are used for consumption. Water, propylene glycol, dipropylene glycol, monomethyl ether, butoxyethanol, deionized water, edible alcohol, ethanol, aqueous LiOH/KOH/urea, Tween 80, and methylcellulose are alternatives to synthetic additives.[23,25,28,43]

Propylene glycol and distilled water were employed as solvents by Sanson *et al.* (2007). Glycols and other alcoholic additions can help disperse the powder since they function as pseudo-surfactants and co-solvents in aqueous solutions. These alcoholic additions mostly have a pseudo-surfactant action at low doses, which causes networks to develop between cellulose and water. However, a co-solvency impact that induces phase separation and disturbs the previously stated networks predominates when employed at high doses.[44] Glycerol is a great cosolvent that is appropriate for edible materials, and employed it as the solvent in their edible ink patent application. A LiOH/KOH/urea combination, a recently created solvent that can dissolve chitosan through a freeze–thaw procedure, was added by Ding *et al.* (2020). It's an environmentally friendly solvent that changes chitosan.[19] The usage of a water/di propylene glycol monomethyl ether combination resulted in a significant maximum shift in the dye's absorbance and a reduction in the dye's solubility, according to Huang *et al.* (2014). The water/2-*n*-butoxyethanol system is the preferred method for creating all-natural inkjet dye inks because it yields colors with better solubility and does not exhibit noticeable variations in the dye's maximum molecular weight.[36]

3. Extraction of colorant from natural sources

Among the many ways of extracting dyes, aqueous extraction is an ancient and traditional method in which the powdered source is soaked in water, boiled, and then filtered.[45] Ultrasonic

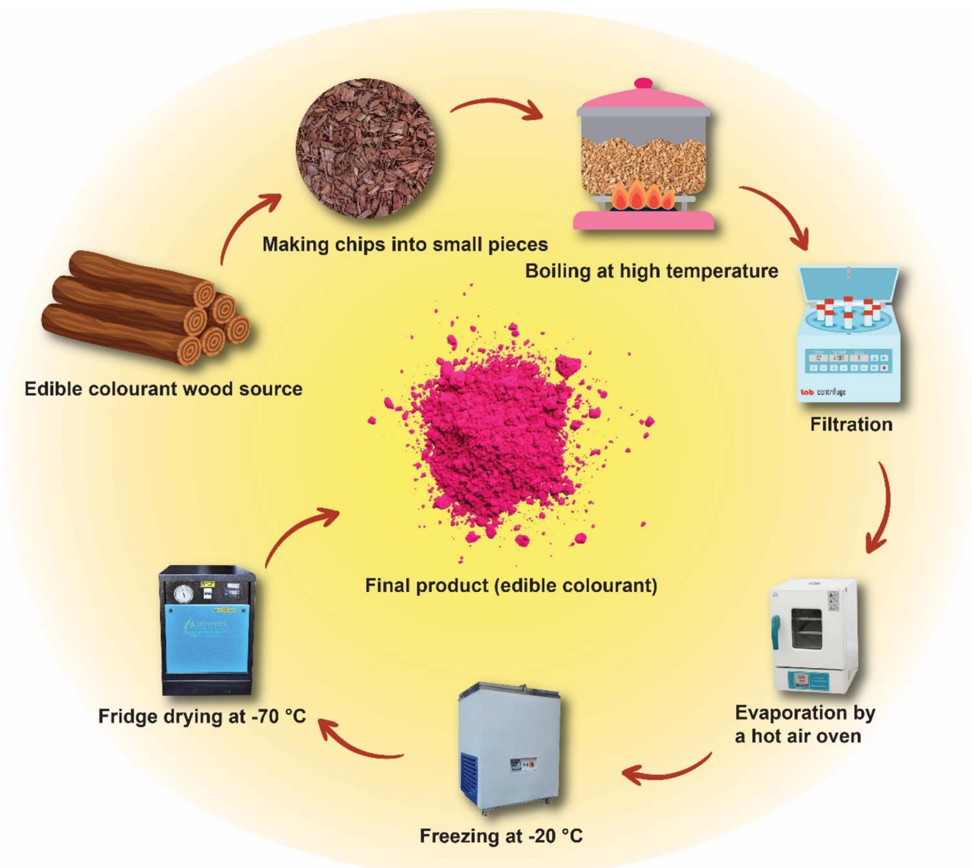

Fig. 1 Extraction of colorants/dyes and preparatory steps in the development of edible colorants, including collecting wood, making chips, boiling, filtering, evaporation, freezing, freeze-drying, powder preparation, and storage.

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extraction, utilizes high power low-frequency ultrasound waves for extraction of the dye; in this method, the powdered form of the plant, along with a mixture of ethanol and water, is placed in an ultrasonic bath and sonicated, following which the liquid is filtered.[46,47] Solvent extraction is the most effective technique for natural dye extraction; ethanol, methanol, acetone, petroleum ether, chloroform, and organic solvents are used in the extraction process.[48] Microwave-assisted extraction (MAE) involves heating solvents in contact with a sample to separate analytes from the sample matrix into the solvent.[49] Alkali or acid extraction, that is, obtains the maximum color yield and boosts because of the hydrolysis of glucosides.[50] Enzymatic extraction and fermentation is an enzyme extraction approach that includes softer extraction conditions and consistent physical and chemical characteristics of active components to obtain optimum natural dye extraction.[50]

The most common and popular technique for colorant extraction is illustrated in Fig. 1. The source of the color is a plant that is dissected into small pieces. The chips are then boiled at high temperatures until all color ingredients are removed from the wood. The colored liquid is filtered *via* centrifugation. The filtered liquid is kept in a hot air oven, and the high-concentration liquid is stored at −20 °C for 24 h. A freeze dryer is used to prepare the powder at −70 °C, which should be stored at −40 °C for future use.

4. Preparation of edible ink

The preparation method of edible ink depends on the composition required, material behavior, and properties. The preparation begins with a colorant, which is mixed with other ingredients such as mordants or color enhancers, binders or resins, solvents, or additives. Ozcan *et al.* (2020) reported a method for producing edible ink where grated red beets were used as the colorant mixed with a water–ethanol mixture and stirred at 200 rpm. The active dye was transferred to the liquid after filtration of the colored liquid. An evaporator was used to remove the solvent at 1500 rpm under vacuum at 50 °C. The mixture was then precipitated at 13 500 rpm for 10 min, and a vacuum dryer was used to prepare the powder.[37]

Ding *et al.* (2020) prepared CMC-based edible ink by dissolving CMC in water; *Monascus* was added as a pigment and stirred at 1500 rpm for 2 h. Different concentrations of CMC were then added. Huang *et al.* (2014)[25] described the preparation of edible ink by mixing dye, water, and humectant and stirring using a magnetic stirrer for 10 min. The ink material was added and stirred for 120 min at 50 °C, following which the additives and solvents were added and stirred for 30 min. Savvidis *et al.* (2014)[24] developed an edible ink using water as the solvent, where the ingredients were stirred for 30 min using a homogenizer at 18 000 rpm.[51] Zhang *et al.* (2016) reported a screen-printing edible ink preparation method in which chitosan, acetic acid, and alcohol were mixed with natural pigments and additives.[38]

Liu *et al.* (2013)[112] patented a preparation method for edible ink, where potassium sorbate was added to distilled water at 50–70 °C in a water bath with stirring. Xanthan gum was added to solution. Soybean oil, food dye, and a heatproof reagent were mixed and named solution B. Solution B was then added dropwise to solution A and stirred for 25–35 min. Wang *et al.* (2009)[111] filed a patent for edible ink preparation, in which shellac was added to ethanol and stirred. Then, an edible iron oxide toner, an auxiliary agent, was added to the shellac solvent, stirred until uniform mixing was obtained, and then ground for 3–5 h. A list of edible inks developed using different colorants, binders, and additives/solvents, and their functional properties (as found in previous studies) are presented in Table 3.

As a popular procedure, a specific amount of pigment or dye is mixed with a solvent (water or ethanol) for 1 h using a magnetic stirrer. The addition of a color enhancer increases the color properties, if required. A binder (CMC, guar gum, or gum Arabic) is prepared in distilled water by stirring at 300 rpm, room temperature, on a hot plate for 1 h. The previously mixed colorant and mordant are added to the binder with stirring for 1 h at 300 rpm.[52] A ball milling machine is used to reduce the particle size of the prepared ink. To maintain the viscosity of the ink samples, water is added slowly to obtain the desired result.[27,31] The preparation method of edible ink is shown in Fig. 2.

5. Properties of edible ink

5.1 Rheological properties

Rheology is an important parameter affecting the application of edible ink. Accurate analysis of ink formulations and rheological performance also provides a preliminary assessment of ink printability, bridging the gap between edible inks and real-world printing. The smoothness of the printing process correlates strongly with the rheological features of viscosity, pseudoplasticity, and shear thinning, which are all closely related to the constituents of the ink (concentration, molecular weight, temperature, pH, and inter- and intra-molecular interactions).[53] The modulus (of storage and loss) indicates the viscoelastic qualities of edible ink (liquid or solid-like behavior) and thus influences the strength of the structure, course of chemical reactions, and resistance to heat, time, and frequency of edible inks. This might be critical for effective printing, and maintaining ink status and structure. Additionally, information regarding yield stress, high compliance, and thixotropy may aid in understanding the status transition, bond orientation, and structure recovery of edible inks.

Guo *et al.* discovered that the viscosity of the buckwheat starch-high-methoxy pectin gel system was reduced by a combination of microwave heating and calcium chloride treatment, which increased the printing precision and self-supporting properties.[54] Rheology may provide insights regarding the structural characteristics of edible inks. According to Riantiningtyas *et al.* (2021), increase in gelatin concentration considerably increased the yield stress, storage modulus, and loss modulus because of the creation of a highly organized gelatin gel network in high-protein yogurt gel.[55] Incorporation of more whey protein isolate softens the yoghurt complex gel and reduces yield stress appropriately, allowing for smooth and continuous extrusion during printing. It is believed

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Table 3 Studies on the development of edible inks from different sources, their compounds (coloring agent, color enhancer, binder, and solvent), and functional properties

Coloring agent	Color enhancer	Binder	Solvent/additives	Properties	Reference
Titanium dioxide	—	Methocel A4M prem, MHEC 1500 PE, MHEP 20000P and carboxymethyl cellulose tylose	Water and propylene glycol	Gas sensors and environment-friendly	23
Annatto, cutch, pomegranate rind and golden dock	—	Alcoosperse LFD and sodium salt	Di propylene glycol, monomethyl ether, butoxyethanol and water	Natural and water-based	24
Tartrazine, allura red, light blue, apple green and composite black	—	Sorbitol and gum Arabic	Deionized water and edible alcohol	Edible, safe, water-based, and environment-friendly	25
Red beet	Potassium alum	Carboxymethyl cellulose	Ethanol	Natural, antimicrobial, pH-sensitive	26
Monascus	—	Carboxymethyl chitosan	Lithium hydroxide, potassium hydroxide, and urea aqueous	Edible, water-soluble, and antimicrobial	27
Titanium dioxide	—	Chitosan	Tween 80 and methylcellulose	Edible and non-toxic	28
Edible carbon black	—	Chitosan	Tween 80, glycerin, soybean oil and beeswax	Excellent fineness, viscosity, initial dryness, tinting strength, and edible	100
Stir dye	—	Resin substitute	Deionized water, alcohol and moderate	Edible, high stability, and good print quality	102
Purple potato	—	Xanthan gum	Sucrose, soybean oil, ethanol, citric acid and distilled water	Excellent color and edible	103
Blueberry dye	—	Chitosan	Distilled water, acetic acid, and chitin nanofiber	Environmentally friendly, degradable and edible	104
Cathay pigments, pigment yellow 42 ($FeO(OH)\cdot xH_2O$)	—	Edible bee wax and chitosan	Tween 80, soybean oil, acetic acid solution, and polyglycerol fatty acid ester	Edible, environment-friendly, antimicrobial, and high print performance	105
Red cabbage juice, lemon juice, orange juice and apple juice	—	Potato starch	Vanillin powder	Anti-cancer, anti-inflammatory, antioxidant, antimicrobial, cardioprotective, anti-diabetic, and vision enhancer	106
Purple potato powder	—	Mushroom scraps	Glycerin, choline chloride, ergosterol, vitamin D_2, methanol, acetonitrile and choline chloride	Good rheological properties	107
Purple sweet potato powder	—	Potato flakes	Sodium alginate, citric acid, sodium bicarbonate and water	Excellent moisture distribution, rheological properties, printing performance, and texture properties	108
FD&C blue no. 1	—	Shellac and polyethylene glycol	Triacetin, glycerol, polysorbate and methylparaben	Optimum viscosity for printing with inkjet printing	1
Coffee	—	Propylene glycol	Glycerol, tween 80 and water	Antimicrobial, suitable for printing on food and edible	109
Edible colourant	—	Shellac	Antifoam agent, propylene glycol, isopropyl alcohol, butanol and preservative	High quality printing and edible	110
Edible iron oxides toner	—	Shellac	Ethanol, sorbyl alcohol, soybean phospholipid, xylitol ester, pectin, gelatin, or bean gum	High adhesivity, low corrosivity, no toxicity, no harm, high oil resistance, high acid resistance, and high color fixing performance	111

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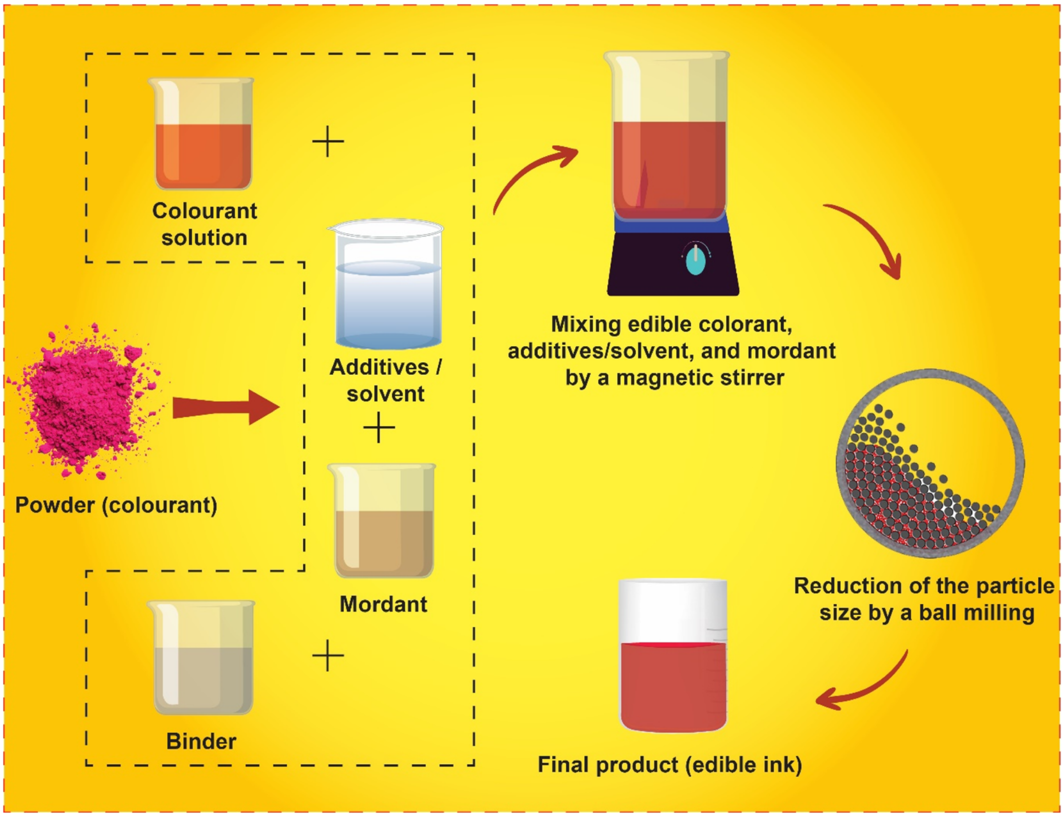

Fig. 2 Schematic representation of the different steps involved in the development of edible ink with colorants, mordants, binders, and solvents from natural sources.

that the synergistic treatment led to aggregation *via* the formation of cross-links between the amide group and Ca^{2+} inside the gel, which in turn induced the release of some of the water attached to the gel matrix, thereby reducing viscosity and increased printing accuracy.[56]

5.2 Antimicrobial activity

Antimicrobial activity plays a key role in active packaging, as it attempts to increase the freshness and shelf life of food, avoid foodborne illnesses, utilize appropriate packaging materials and techniques, increase food safety, lower production and consumption losses, and create environment-friendly packaging.[53] The antimicrobial activity of printed edible ink on paper for the packaging of food products may be measured using the disc diffusion method, in which *Escherichia coli* and *Staphylococcus aureus* cultures are activated by inoculation in tryptic soy broth (TSB), which is maintained at 37 °C for 24 h. Using the spread plate approach, the inoculum (0.1 mL) is applied to the surface of Mueller–Hinton (MH) agar Petri dishes. Next, films 6 mm in diameter are added to the Petri dishes. The same procedures are used to prepare the control samples. The Petri dishes and control samples are placed on a disc film and incubated at 37 °C for 24 h.[57] Following incubation, the inhibition zones around the disc films are analyzed qualitatively and quantitatively. A quantitative evaluation is performed based on the diameter of the inhibitory zone. The area surrounding the disc film is a measure of bacterial growth inhibition.

Ozcan *et al.* prepared an edible ink with red beet and tested it against Gram-negative (*Escherichia coli*) and Gram-positive (*Staphylococcus aureus*); the ink showed significant antimicrobial activity. Studies on new and improved packaging concepts with attributes such as edibleness, affordability, biocompatibility, and antibacterial activity have increased recently, both for product packaging and the product itself. Red beet, cabbage, and onions, which are used to make natural ink, are examples of plants with antibacterial properties.[37] Ding *et al.* developed CMC-based edible ink and found significant antimicrobial activity against Gram-positive and Gram-negative bacteria. The exceptional antibacterial properties of these inks have encouraged their use, particularly in the food industry.[51]

6. Printing techniques for edible ink

6.1 Screen printing

The screen-printing method is the most suitable and cost-effective among all printing techniques, which allows printing on any substrate, including uneven substrate, food, circuits, printed electronics, electrodes, and curved surfaces. It is associated with benefits such as low-temperature manufacturing, minimal processing steps, inexpensive mass production, high speed, simplicity, adaptability, and low cost as it is relatively

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quick and versatile. A screen, stencils, squeezers, ink, pressure, and printing speed are the main components of the screen-printing process.[58] Even with a fairly basic printing method, several factors such as printing speed, angle, squeezer geometry, screen-to-substrate distance, mesh size, and ink freshness significantly impact the properties and qualities of the printed image. Gooey line resolution can be achieved even with low-viscosity inks if the critical surface tension of a substrate is lower than the surface energy of the inks. The force generated when utilizing a steel net for stencil marking is known as screen tension.[59] Maintaining the same printing conditions across the entire region of the screen is critical for printing color filters uniformly over a broad area. Understanding the interactions between finely ground squeegees, and the use of suitable ink formulation, printing process technology, screens with fine mesh, and precision screen printers renders this achievable.

Zhang *et al.* investigated edible screen-printing ink with chitosan and found that high-quality print and outstanding qualities included fineness, viscosity, initial dryness, tinting strength, and substrate adherence. Wang *et al.* used a screen-printing technique to develop edible ink on coated paper, nori, and chocolate.[60] Chitosan–TiO_2-based edible ink was also printed by the same researcher using the screen-printing method. Ding *et al.* utilized a screen-printing method for the prepared CMC-based edible ink on a variety of substrates, irrespective of their size, such as Chinese spinach, potato, bread, white radish, wonton skin, grapefruit, sheet of bean curd, piece of pig rind, chocolate, and paper. Food screen printing has been shown to be effective, with excellent visual recognition.[61]

6.2 Flexographic printing

Modern printing methods are used to produce packaging labels and print on different substrates using edible inks. Flexographic printing, which is used extensively in the packaging industry, has the highest economic potential of all the techniques because of its high throughput and low production costs. Flexible packaging, multiwall bags, labels, corrugated packaging, printed electronics, ZnO ink printing, and gas and biosensors are all produced using the fundamental long-established roll-to-roll printing technology of flexographic printing. Flexographic printing can be performed on delicate surfaces with simplicity and efficiency. Its printing performance in the food industry is directly related to the rheology of the edible inks.[62] Anilox rollers and polymer plates are the foundations of the printing process. A cylinder, called an anilox roller, is used to etch the microscopic cells. The capacity of the anilox rollers, measured in $cm^3\ m^{-2}$, is determined by the depth and form of these cells. The procedure involves printing a graphic artwork created by the highest points on the polymer plate. Ink is first transmitted from the anilox roller to the polymer plate during the flexographic printing process, and then from the polymer plate to the printing substrate. The volume of ink transferred onto the substrate typically ranges between 0.25 to 6 m and is mostly influenced by the anilox roller's capacity and the viscosity of the ink. Currently, this printing method is used for more than 75% of packaging products.[63,64]

Palo *et al.* scrutinized the flexographic printing method for printing on an edible substrate and considered it a potential technique for creating solid nanoparticulate systems with improved dissolution characteristics. Because of proper viscosity, the CMC-based edible ink for flexographic printing demonstrated clear shear thinning behavior, and the choice of medium yield stress (2.994 Pa) rendered printing reasonably simpler than that using ink with larger yield stress that tends to block the anilox rollers. Flexographic printing of edible inks with CMC as the basis produced images of bean curd and wonton skin, which had good color saturation and outstanding visual recognition, as shown by Cheng *et al.* Similarly, Wang *et al.* (2018) developed a chitosan-based flexographic ink that is renewable, edible, and has excellent printable properties for a wide range of applications. Fuyuan *et al.* used a flexographic printing technique to print edible inks based on CMC for food packaging, which provided a high-quality image with outstanding visual recognition.[65]

6.3 Inkjet printing

The inkjet printing process, which is a non-contact method, is a common technique for printing edibles. The process of edible printing by inkjet involves application of graphics and edible food colors to various food products, including candy, cakes, cookies, pastries, and even meals. The market for edible printing has expanded because of improvements in digital printing technology and consumer demand. It is the best method for printing on the surface of food and drugs because of its flexibility, high speed, intelligence, low cost, and lack of pollution.[25] The evolution of inkjet printing technology depends on the ability to manage drop conditions, which are mostly determined by viscosity. Images were printed on icing and edible paper sheets that were applied to cakes using inkjet printers with edible ink cartridges.[66] Print quality is becoming increasingly crucial as the edible printing market continues to expand. Customers prefer small, readable text, and color-accurate representations of photos.

The 2D printing of food involves the use of printing techniques to decorate food surfaces. Inkjet printing is often considered a suitable printing technique, as food is a particularly demanding substrate for printing.[67] Both the EU and FDA have broadly accepted inkjet printing for use in food decoration, and compatible printing systems and edible inks are readily accessible in the market. Additionally, inkjet printing is simple to automate, appropriate for mass production, provides the opportunity for customized and personalized labeling, and can be incorporated into current food manufacturing lines. A liquid-binding substance was selectively deposited on a powder bed using an inkjet printer. The area was then covered with a thin layer of powder. This procedure is repeated until all the layers are finished.[68]

Young *et al.*[113] fabricated a device with a bubble-jet printer head assembly and a container for holding a liquid food colorant suitable for printing an image, as described previously,

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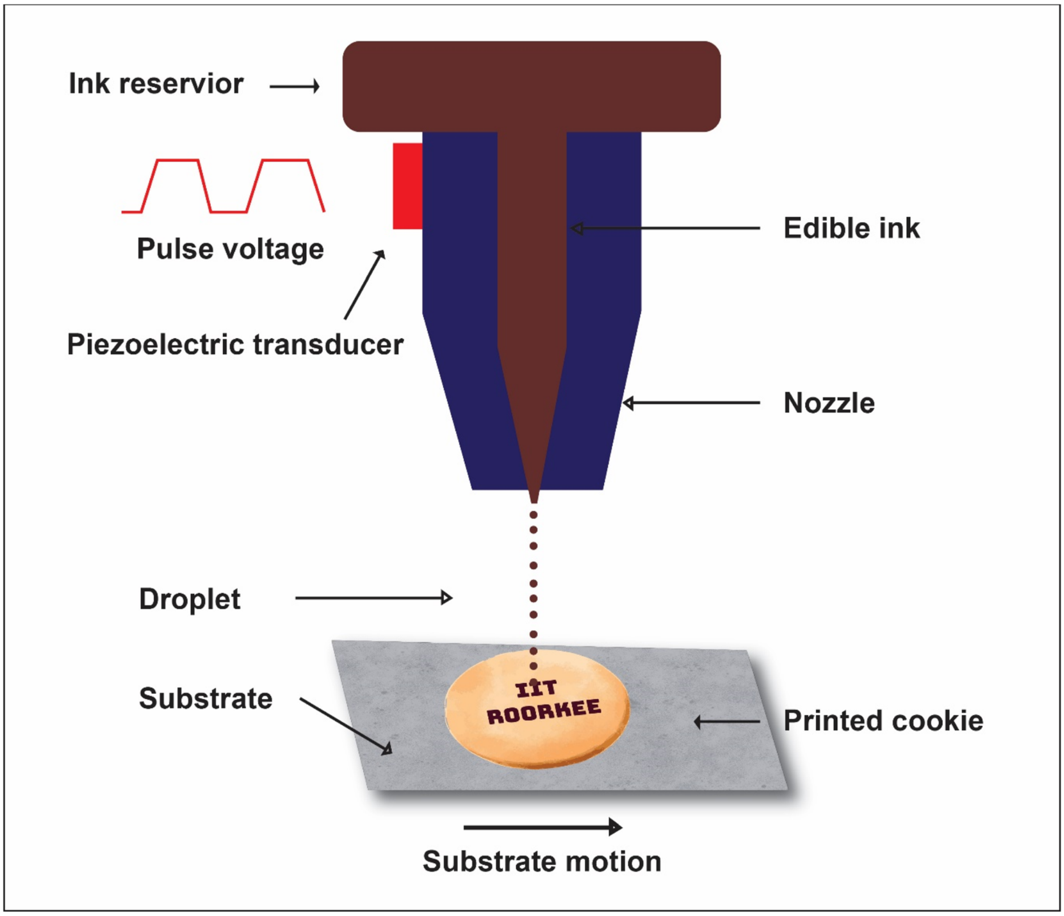

Fig. 3 Graphical illustration depicting printing of edible ink on a food substrate using an inkjet printer.

onto the surface of an edible substrate. The use of a high-polarity water-based glaze or polishing gum to modify the surface of an edible improves the printing of images on the edibles using low-viscosity inks normally used in inkjet printing, according to a patent filed.[69] Genina *et al.* claimed that inkjet technology with programmable printing parameters offers a promising approach for creating customized dosages on various substrate types, which has the potential of creating drug delivery systems with the necessary properties.[70] A graphical illustration depicting the printing of edible ink on the food substrate using an inkjet printer is shown in Fig. 3.

7. 3D printing using edible ink

3D printing is an additive manufacturing or fabrication technique that combines engineering, materials science, and computer-aided design (CAD) technologies. It is a digital manufacturing method that creates 3D structures and objects by tailoring the material composition, processing settings, and item geometries at each stage. Extrusion, melt deposition, optical immobilization, vat photo-polymerization, material jetting, binder jetting, powder bed fusion, sheet lamination, selective sintering, extrusion, binder injection, and inkjet 3D printing are some of the several types of 3D printing technologies. 3D printing has a wide range of applications, including those in food, medicine, aircraft, automobiles, military, and space manufacturing sectors. Additionally, 3D printing has the potential to decrease postharvest and post-processing food waste and extend the shelf life of food. It can alter nutritional content, texture, adaptability in design, and reduction of waste, enable rapid prototyping, personalization, and use of novel geometrical shapes, and enhance diversity, quality, healthiness, and sustainability.[71]

Major issues with 3D printing include printing time, speed, accuracy, and quality, especially for food and relatively new platforms. Further studies are required to overcome these constraints and improve the printing process, particularly for food applications. Most reviews on 3D food printing technologies and processes that have been published so far have focused on process variables, such as nozzle diameter, height, infill layer, printing speed, material properties, gel strength, glass transition temperature, rheological properties, and mechanical properties. Toxicity and food safety of edible ink or edible materials should be researched fully before using them for 3D printing.[72–75] By extruding a paste consisting of starch, sugar, yeast, corn starch, and cake icing, "cake mixes" were first printed using 3D food printing. When used in 3D food printing, high concentrations of starch, which has good shear stability,

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helps maintain the shape of the deposited structure because of the interaction between starch molecules.[65]

Severini *et al.* used fruits and vegetables in 3D food printing. Mantihal *et al.*[114] used chocolate as a prototype edible ink to create 3D structures. The only way to make the material printable is to incorporate MgST, which improves the flow of the substance and lubrication during printing. The major variables affecting 3D printing accuracy are print model selection, printing parameter optimization, and edible ink material qualities or modifications in their formulations. We must consider how the presence of food components, such as starch, protein, fat, cellulose, and moisture, affects the accuracy of 3D printing. The right printing parameters must be chosen depending on the material characteristics of the edible ink to ensure precise printing. The direction of the printing path varies dramatically, which can result in a rough surface of the 3D-printed object. The physical characteristics of the food materials, printing settings, and print models are together essential for generating a 3D printed object of choice.[76] Armstrong *et al.* used cellulose nanocrystals (CNC) to promote thixotropic rheological behavior in foodstuffs, making food items that are not naturally printable using direct ink write (DIW) 3D printing; this method is affordable, and it lays the foundation for developing various material options, making it a popular choice for edible 3D printing.[77]

Wang *et al.* (2023) showed that Pickering emulsion gels can be used as edible inks in 3D printing applications. Chitosan was used to modify the functional properties of the edible inks, and the polymer-crosslinked Pickering emulsions created were used as innovative edible inks for 3D printing of functional food products.[78] Sun *et al.* (2015) filed a patent on a 3D printing method and system for producing food products that are both nutritionally sound and minimal in calories, and claimed that it may be used to produce a nutrient-rich low-calorie food product by including at least one edible non-caloric material and one nutritional material, and then depositing the formulation(s) in the desired form using 3D printing. This creates a food product with a predetermined texture, nutritional value, and caloric content.[79]

8. Food printing application

The priority of edible ink is topmost in the food packaging industry because of its non-toxicity. Food printing and food coating is another field in which edible ink has been successfully used owing to its low cost and easy accessibility.[80] Edible ink on food coatings provides a premium look, improves the strength of food products, lowers particle segmentation, optimizes the tactile and visual characteristics of food surfaces, increases shelf life, and protects against microbial growth and oxidation.[81]

8.1 Cakes

On important days, cakes are frequently decorated as celebration symbols. However, cake decoration requires talent, which is usually done by experts. Modern bakeries automate cake design using machines; however, consumers find it challenging to customize and use such tools. Cookies and cakes are increasingly often decorated with printed embellishments since consumer-grade inkjet printers that print 2D designs using edible ink on sheets and plates have recently become more affordable. In 2020, Miyatake *et al.* presented a novel 3D printing method that use whipped cream to produce customized ornamental designs. Edible sheets, sometimes called frosting or icing sheets, are used in picture cakes by a cake-printing machine using edible ink to customize the cake-printing business.[82]

8.2 Confectionary

Edible ink is also used in the confectionery industry to print designs on chocolates and other sweet treats. The designs were printed onto chocolate transfer sheets using a laser printer, and the transfer sheet was then placed onto the chocolate surface. The design is then transferred to the chocolate, creating an impressive custom look. Confectionary items such as chocolate, cookies, toffee, candy, and biscuits are printed with edible ink using a digital printing technique, which helps the consumer experience personalized shapes and exciting decorations. The significance of the printing procedure and platform in chocolate printing, which has been the subject of a more recent study, includes algorithms for adjusting the layer thickness and scanning speed to increase the printing efficiency and quality.[57]

The Waseda University has created an electrostatic inkjet printer that uses a nozzle with a thin ABS resin fiber at the tip to reduce the droplet size and print chocolates <50 μm in thickness with great precision.[83] Unlike sintering, which would probably require a significantly lower fat content than is typical of chocolate, inkjet printing can handle viscous materials; therefore, chocolate and cookies can be printed without the need for flow enhancers or changes in their composition. However, whether inkjet printing can be truly classified as a 3D printing technology is questionable, because it is frequently used to produce simpler 2D designs.[84]

8.3 Fresh fruits

The demand for edible ink is gradually increasing in the printing of food and is an alternative to strikers on fruits and vegetables. Edible ink or coatings are used in fresh fruits to enhance their functional properties and cosmetic purposes. Edible ink on food coatings provides a premium look, improves the strength of food products, lowers particle segmentation, optimizes the tactile and visual characteristics of food surfaces, increases shelf life, and protects against microbial growth and oxidation.[81] The new POLY trusts edible UV invisible and visible inks from the Australian business, Digital Ink Technologies, provide a distinctive way of naming fruits and vegetables. The company's printers can now use polymer thermal inkjet technology, in which the ink clings firmly to the produce and is difficult to remove with rubbing alcohol. Growers or distributors can print using HACCP-certified edible inks that are either invisible or visible to consumers. Edible ink labeling on individual fruits such as apples, oranges, stone fruit, or even kiwi fruit with a “Best Before the date,” “Picked Date,” or even a “LOGO” can be printed.[85] Ding *et al.* (2020) used screen printing to print his developed edible ink on

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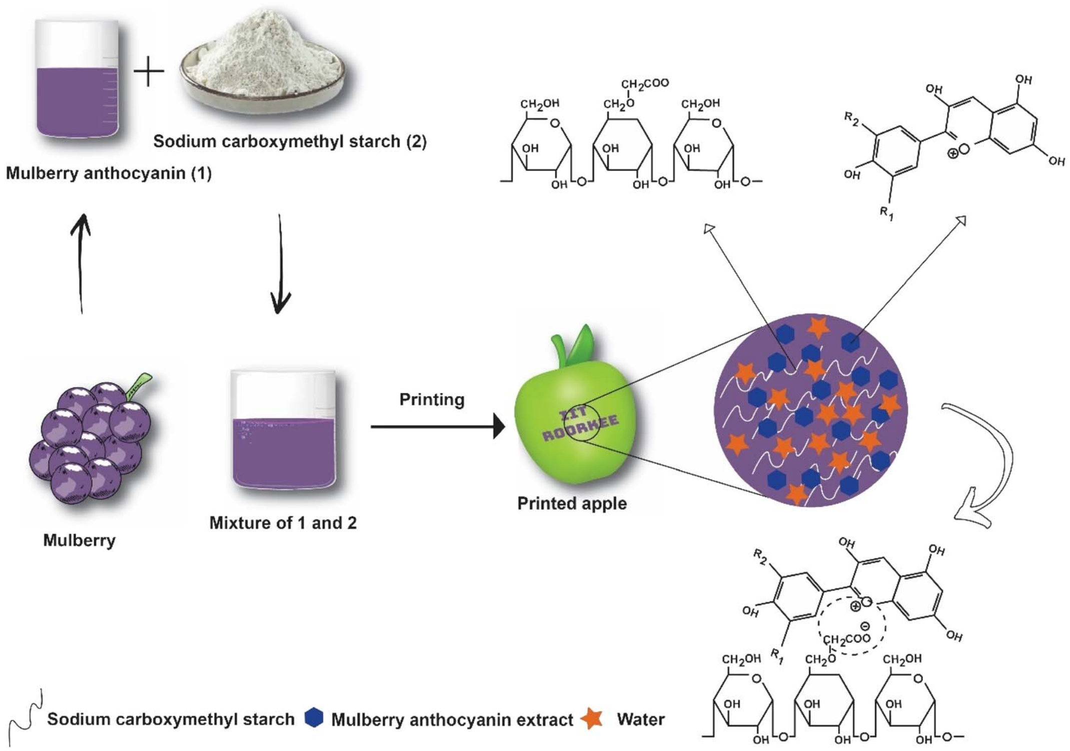

Fig. 4 Graphical representation of the possible chemical interactions among colorants, binders, and solvents of mulberry anthocyanin extract-based edible ink printed on green apples.

different fruits and vegetables, such as wonton skin, potato, Chinese cabbage, and grapefruit.[51] Morelos *et al.* (1996) patented an inkjet printing ink that can be printed on fruits and vegetables.[86] A graphical representation of the possible chemical interactions among colorants, binders, and solvents of mulberry anthocyanin extract-based edible ink printed on green apples is shown in Fig. 4.

8.4 Others

Printing on pills and capsules. Edible ink can be used to print information such as the name of the medication, dosage, and expiration date directly onto pills and capsules, making it easier for patients to identify and monitor their medications. The use of edible ink is becoming popular in medical packaging, as commercial ink is associated with a migration problem; however, edible ink is completely safe and edible.[51] Printing on pills and capsules: edible ink can be used to print information such as the name of the medication, dosage, and expiration date directly onto pills and capsules, making it easier for patients to identify and monitor their medications.

Edible cups and plates are available in the market owing to their sustainable approach and alternative to single-use plastic; however, these disposables are currently not printed due to the unavailability of proper ink.[87] Thus, edible ink is the only solution to overcome this problem; in addition, it will provide a brand name and other important information.[88,89] Printing on eggs with edible ink appears to be a premium and exciting idea. In addition to food, edible ink can be used on paper, edible films, and packaging of direct-contact food. Printing paper with edible ink reduces costs and prevents harmful issues.[90] Edible ink on paper is another extensive field that can change the world in terms of sustainability. Ding *et al.* investigated printing with edible ink on coated and uncoated paper using screen printing and flexographic methods, and found excellent quality of printing with optimum pH, optical density, scratch resistance, contact angle, and chromatic values, which was a remarkable achievement for the printing industry. Edible ink is primarily designed for use in the food and confectionery industries, although some potential applications of edible ink are available for non-food items. The following are some of the examples.

(1) Printing on non-food items for decorative purposes. Edible ink can be used to print non-food items such as paper, plastic, and fabric, providing a unique and colorful decorative effect. This can be used in a variety of settings, such as creating custom designs for t-shirts or other apparel.

(2) Printing on temporary tattoos. Edible ink can also be used to print temporary tattoos on the skin, creating a fun and safe way of decorating the body for parties or other events. Ink is non-toxic and safe for human consumption, making it a good option for those with sensitive skin.

(3) Printing on packaging materials. Edible ink can be used to print packaging materials, such as paper bags or boxes, providing a custom and eye-catching design. This could be useful for companies seeking to brand their products or for creating unique packaging (Hakim *et al.*, 2023).[12]

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(4) Printing on craft items. Edible ink can be used to print a variety of craft items, such as wooden blocks, pottery, or other items that require a durable and long-lasting design.

Overall, while edible ink is primarily used in the food industry, it can be used creatively in a variety of non-food applications. Its versatility and nontoxic properties make it a good option for a range of decorative and branding purposes.[32,91]

9. Challenges with edible ink

The availability of edible ink is the main challenge impeding its use; many scientists are experiencing a critical situation in collecting all the ingredients of ink that are edible. The cost of edible ink is the key factor that demotivates end users, although in the real scenario, it can be minimized under certain conditions. Owing to the nascent nature of the technology, monotony of the color used, and high cost, the application of these edible inks is still limited and more research is required to circumvent these problems. Printing using screen printing techniques on curved food substrates is challenging and time-consuming, and alternative printing methods have to be developed. Lightfastness and rub resistance can be difficult to control because of the nature of edible materials.[92] Maintenance of viscosity can be challenging for storage and long-term use when drinkable solvents such as water are used. Furthermore, it is difficult to ensure that the conditions for long-term storage are safe and reliable.

Molding of 3D food-printed edible materials is difficult. Surface tension may cause water to create a boundary layer around the solids in the 3D food printing material under microgravity, which can immediately hamper the printability of the 3D food printing material. To minimize the effects of microgravity and material constraints, easy implementation of product post-processing steps must be considered.[93] The need to manufacture multicolored, multi-flavor, and multi-structure products, print with precision and accuracy, ensure process productivity, and other factors have impeded the widespread application of this technology in the food industry.[94] Poor ingredient flow behavior can impact the structural accuracy, shape stability, and compatibility with conventional food processing such as baking, drying, and frying. However, from a process perspective, the major concerns are throughput, speed, layer distortion or shift when printing vertically, sliding phenomena, and material deformation during printing.[95] A deeper understanding of the impact of additives on rheology and printability is required to maximize customization. Alternative methods of achieving high performance and printability, including dehydration or temperature control in pre-processing and printing steps, should also be found to reduce costs and the textural or flavor changes associated with the use of these additives.[96]

10. Future trends for edible ink

As technology continues to advance, future trends in edible ink are expected to bring exciting new possibilities. The use of natural and plant-based ingredients in edible ink is one of the most significant trends. Consumers are becoming more conscious of the food they consume and are seeking healthy and sustainable options. This trend is expected to drive the development of edible inks using natural colorants derived from fruits and vegetables. This will also provide new opportunities for customization, as consumers can choose specific colors and flavors for their printed food items.

Another trend is the development of 3D food printing technology. 3D printing allows the creation of intricate designs and shapes that were previously impossible with traditional food preparation methods. The use of edible ink in 3D printing will enable the creation of customized and personalized food items on a whole new level. From personalized cakes to intricately designed chocolate sculptures, these possibilities are endless.

In addition, the development of smart packaging is another trend in the field of edible inks. Smart packaging is a technology that can monitor and track the condition of food inside a package. This can include information on the temperature, humidity, and freshness of the food. Edible ink can be used to print sensors and other electronics in food packaging, making it easier for consumers to monitor food and reduce food waste.

Finally, the use of edible ink in the pharmaceutical industry is increasing. Edible ink can be used to print information directly onto drugs, making it easier for patients to take medications. This technology is especially useful for children and elderly patients who may have difficulty in swallowing pills.

11. Conclusions

The main variables influencing the accuracy of food printing are the properties or formulation adjustments of the edible ink material, optimization of printing parameter, and choice of print model. Edible ink printing on food or edible surface applications is crucial because of the different aspects related to food quality and safety assurance. For example, the migration of edible ink at the molecular level is a critical point because of its compatibility issue with other edible materials. The ink source is the primary factor that ensures the safety and wholesomeness of food after printing. Natural sources containing pigments of different colors are potential sources of edible ink. Extraction from the plant or flora source depends on different factors such as the solvent, extraction techniques, and drying methods for the powdered form of the ink. In addition to the preparation of edible inks, the physical and rheological parameters of the ink also play crucial roles in their application on different surface structures. The printing methods will also be a deciding factor that ultimately determines the design part of the information on the food surface. The feasibility and economic aspects of the printing method will ensure control of the pricing of products with edible printing. In addition to the vigilance over the characteristics of food materials, optimization of the printing parameters should also be considered equally important. Based on the material properties of the edible ink, proper printing parameters must be chosen to achieve accurate printing. Furthermore, we must consider how the presence of food components, such as starch, protein, fat, cellulose, and moisture content, affects the accuracy of 3D printing.

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Author contributions

The authors jointly conceptualized the study design. Lokman Hakim searched for and resolved conflicts and wrote the first draft. Ram Kumar Deshmukh charted the data. Youn Suk Lee and Kirtiraj K. Gaikwad led the analysis and writing, and incorporated critical feedback from all authors.

Conflicts of interest

The authors declare that they have no conflict of interest.

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